Static Microfield Printing at BL12 with Advanced EUV Lithographic Optics

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1. INTRODUCTION

Extreme ultraviolet (EUV) projection lithography is now the leading contender for *next-generation lithography* beyond the limits imposed by currently used refractive optical systems. Because EUV systems utilize resonant reflective coatings,[1] at-wavelength characterization,[2] including system wavefront metrology, has played an essential role in the development of EUV lithographic optics.

To meet the at-wavelength wavefront metrology challenge, an EUV-compatible diffraction-class interferometer, the phase-shifting point diffraction interferometer (PS/PDI), has been developed and implemented at Lawrence Berkeley National Laboratory.[3] As described in a separate abstract in this compendium, the PS/PDI has been demonstrated to have a wavefront measurement accuracy of better than $\lambda_{EUV}/200$ (0.67 Å) within a numerical aperture (NA) of 0.1.[4]

While PS/PDI wavefront interferometry[5-7] is now routinely used for the characterization and alignment of EUV lithographic optics,[8,9] the ultimate performance metric for lithographic systems is printing in photoresist. Direct comparison of imaging and wavefront performance is also useful for verifying and improving the predictive power of wavefront metrology under actual printing conditions. To address these issues in the most flexible and time-efficient manner, static, microfield printing capabilities have been added to the EUV PS/PDI. In printing configuration, the test station is referred to as the Static Exposure Station (SES). This at-wavelength test station has been designed to test the 4×-reduction projection optics boxes[9] developed for implementation in the EUV Engineering Test Stand (ETS)[10] now operational at the Virtual National Laboratory (the VNL is a partnership between Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories).

Two EUV 4×-reduction optic systems have been developed as part of the EUV LLC's EUV lithography program with the first developmental set of optics (the Set-1 optic) currently operating in the ETS.[11] The second much higher quality optic[4,12] (the Set-2 optic) is currently undergoing microfield static printing characterization in the SES. Although this optic is destined for integration into the ETS for full-field scanned imaging, valuable early learning has been obtained by the new microfield static printing capabilities of the SES.

A static imaging system, the SES has a microfield size of approximately 100 μm at the wafer. However, the full 1-inch arc field can be covered one microfield at a time by moving the entire system relative to the stationary illumination beam. The SES works with the same reflection masks used in the ETS. In addition, the SES supports variable partial coherence (σ) ranging from approximately 0 to 1 as well as enabling a programmable pupil fill.

The biggest challenge for the implementation of printing capabilities at the EUV interferometry beamline was modifying the illumination coherence. Relevant printing studies with lithographic optics require illumination partial coherence (σ) of approximately 0.7. This σ value is very different from the coherent illumination requirements of the EUV PS/PDI and the coherence properties naturally provided by synchrotron undulator beamline illumination (<0.05).[13,14] Adding printing capabilities to the PS/PDI experimental system has thus necessitated the development of a novel illumination system capable of quantitatively reducing the inherent coherence of the beamline.

1. ADDING PRINTING CAPABILITIES TO THE PS/PDI

Although the illumination issue is the most fundamental of the changes required to implement printing in the EUV interferometry tool, several other modifications were necessary to enable printing in a system originally designed for interferometry.

In contrast to the transmission configuration of the PS/PDI,[3] relevant printing studies require a reflection mask (reticle) to be used and, therefore, the illumination must come from below the object plane. This is achieved by providing clearance for the beam to pass downward through the object plane before it is redirected upward to illuminate the reflection reticle (Fig. 1). The final illuminator optic used to redirect the beam upward is positioned at the location normally occupied by the PS/PDI grating.

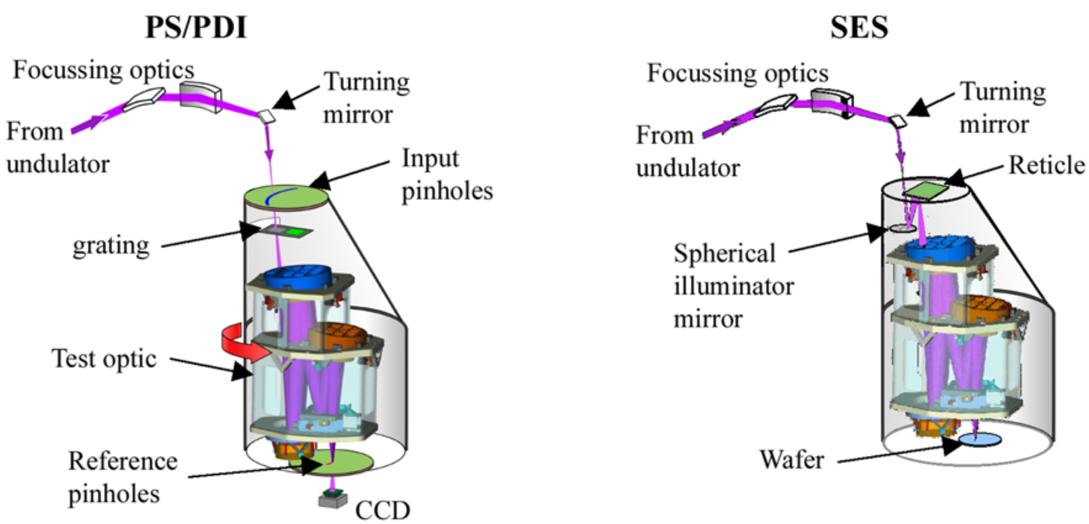

Fig. 1. Schematic of at-wavelength system characterization test stand in both PS/PDI and SES modes. PS/PDI endstation in interferometry mode. In SES mode, the beamline illumination passes through the object plane and is redirected upward using a spherical mirror that replaces grating used in interferometry mode.

Another important issue for the SES was image-plane-stage speed. The original flexural, picomotor-driven stage design was optimized for extremely high resolution (better than 10 nm) at the expense of speed (the original stage speed was approximately 1 μm/s). In imaging mode with no overlay capabilities, however, stage resolution is not important; yet having improved stage speed enables the acquisition of focus-exposure matrices (FEM) in a reasonable amount of time. To address the lateral-scanning speed issue a nested-stage solution has been implemented providing a 20× increase in stage speed while maintaining accuracy when required. This new stage design enables the acquisition of large FEMs (13×13) in approximately 1 hour.

Also newly implemented for printing operation were an electrostatic chuck for the wafer and a vacuum load-lock wafer-transfer system.

1. PRINTING CHARACTERIZATION

The ETS Set-2 optic[9] is a 0.1 numerical aperture (NA) optic designed for 100-nm critical dimensions (CD). At the central field point, where all subsequent printing results are presented, the Set-2 optic has a wavefront quality of 0.69 nm or 52 mwaves. A detailed description of the interferometric characterization of the Set-2 optic can be found in Refs. 4 and 12.

Although designed for 100-nm CD, the Set-2 optic is capable of higher-resolution performance. Figure 2 shows a series of equal line-space images ranging from 90-nm CD down to 60-nm CD. All images were recorded with conventional disk illumination and a partial coherence of 0.8. In Fig. 3 equal line-space printing down to 50-nm is demonstrated. This was achieved using resolution-enhancing dipole illumination, created by the novel coherence-controlling illuminator. This illumination improves the resolution in the vertical direction at the expense of other orientations.

In addition to using resolution-enhancing illuminations, it is also possible to decrease printed-line size for loose-pitch features through dose control. Figure 4 shows 39-nm 3:1 pitch elbows printed by overdosing features coded as 80-nm 1:1 on the reticle. These results were obtained using conventional disk illumination with a partial coherence of 0.7.

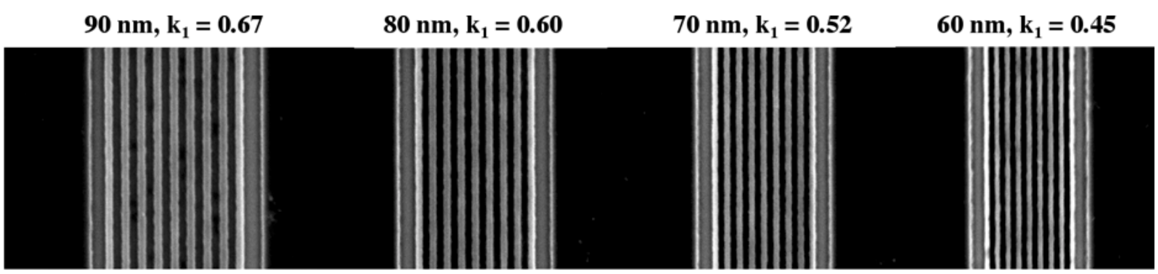

Fig. 2. Series of dense-line images ranging from 90-nm CD down to 60-nm CD. All images were recorded with conventional disk illumination and a partial coherence of 0.8.

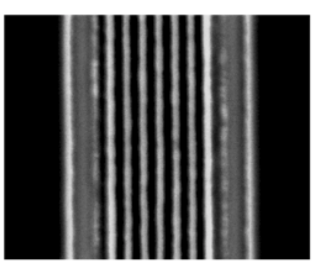

Fig. 3. 50-nm dense line printing ($k_1 = 0.37$) achieved with dipole illumination.

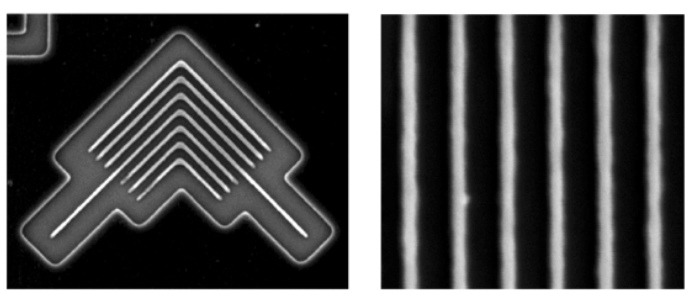

Fig. 4. 39-nm 3:1 pitch elbows and lines printed by overdosing features coded as 80-nm 1:1 on the reticle. Conventional disk illumination with a σ of 0.7 was used.

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